

# The NUBASE evaluation of nuclear and decay properties\*

G. Audi<sup>a,§</sup>, O. Bersillon<sup>b</sup>, J. Blachot<sup>b</sup> and A.H. Wapstra<sup>c</sup>

<sup>a</sup> *Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, CSNSM, IN2P3-CNRS&UPS, Bâtiment 108, F-91405 Orsay Campus, France*

<sup>b</sup> *Service de Physique Nucléaire, CEA, B.P. 12, F-91680 Bruyères-le-Châtel, France*

<sup>c</sup> *National Institute of Nuclear Physics and High-Energy Physics, NIKHEF, PO Box 41882, 1009DB Amsterdam, The Netherlands*

---

## Abstract

This paper presents the NUBASE evaluation of nuclear and decay properties of nuclides in their ground- and isomeric-states. All nuclides for which some experimental information is known are considered. NUBASE uses extensively the information given by the “Evaluated Nuclear Structure Data Files” and includes the masses from the “Atomic Mass Evaluation” (AME, second part of this issue). But it also includes information from recent literature and is meant to cover all experimental data along with their references. In case no experimental data is available, trends in the systematics of neighboring nuclides have been used, whenever possible, to derive estimated values (labeled in the database as non-experimental). Adopted procedures and policies are presented.

AMDC: <http://csnwww.in2p3.fr/AMDC/>

---

## 1. Introduction

The present evaluation responds to the needs expressed by the nuclear physics community, from fundamental physics to applied nuclear sciences, for a database which contains values for the main basic nuclear properties such as masses, excitation energies of isomers, half-lives, spins and parities, decay modes and their intensities. A

---

\* This work has been undertaken with the encouragement of the IUPAP Commission on Symbols, Units, Nomenclature, Atomic Masses and Fundamental Constants (SUN-AMCO).

§ Corresponding author. *E-mail address:* [audi@csnsm.in2p3.fr](mailto:audi@csnsm.in2p3.fr) (G. Audi).

requirement is that all the information should be properly referenced in that database to allow checks on their validity.

One of the applications of such a database is the “Atomic Mass Evaluation” (AME) in which it is essential to have clear identification of the states involved in a decay, a reaction or a mass-spectrometric line. This is the main reason for which these two evaluations are coupled in the present issue. Furthermore, calculations requiring radioactive parameters for nuclear applications (e.g. reactors, waste management, nuclear astrophysics) need to access this basic information on any nuclide. In the preparation of a nuclear physics experiment, such a database could also be quite useful.

Most of the data mentioned above are in principle already present in two evaluated files: the “Evaluated Nuclear Structure Data Files” (ENSDF) [1] and the “Atomic Mass Evaluation” (AME2003, second part of this issue). The demand for a database as described above could be thus partially fulfilled by combining them in a ‘horizontal’ structure (which exists in the AME, but not in ENSDF). NUBASE is therefore, at a first level, a critical compilation of these two evaluations.

While building NUBASE, we found it necessary to examine the literature, firstly, to revise several of the collected results in ENSDF and ensure that the mentioned data are presented in a more consistent way; secondly, to have as far as possible all the available experimental data included, not only the recent ones (updating requirement), but also those missed in ENSDF (completeness requirement). This implied some evaluation work, which appears in the remarks added in the NUBASE table and in the discussions below. Full references are given for all of the added experimental information (cf. Section 2.7).

There is no strict cut-off date for the data from literature used in the present NUBASE2003 evaluation: all data available to us until the material was sent (November 19, 2003) to the publisher have been included. Those which could not be included for special reasons, like the need for a heavy revision of the evaluation at a too late stage, are added in remarks to the relevant data.

The contents of NUBASE are described below, along with some of the policies adopted in this work. Updating procedures of NUBASE are presented in Section 3. Finally, the electronic distribution of NUBASE and an interactive display of its contents with a World Wide Web Java program or with a PC-program are described in Section 4.

The present publication updates and includes all the information given in the previous and very first evaluation of NUBASE [2], published in 1997.

## 2. Contents of NUBASE

NUBASE contains experimentally known nuclear properties together with some values estimated by extrapolation of experimental data for 3177 nuclides. NUBASE also

contains data on isomeric states. We presently know 977 nuclides having one or more excited isomers according to our definition below. In the present evaluation we extended the definition of isomers compared to NUBASE'97 where only states with half-lives greater than 1 millisecond were considered. In present mass spectrometric experiments performed at accelerators, with immediate detection of the produced nuclei, isomers with half-lives as short as 100 ns may be present in the detected signals. We aimed at including as much as possible all those which play or might play in the near future a *rôle* in such experiments. We include also the description of those states that are involved in mass measurements and thus enter the AME2003.

For each nuclide ( $A, Z$ ), and for each state (ground or excited isomer), the following quantities have been compiled, and when necessary evaluated: mass excess, excitation energy of the excited isomeric states, half-life, spin and parity, decay modes and intensities for each mode, isotopic abundances of the stable nuclei, and references for all experimental values of the above items.

In the description below, references to papers that are also quoted in the NUBASE table are given with the same Nuclear Structure Reference key number style [3]. They are listed at the end of this issue (AME2003, Part II, p. 579).

In NUBASE'97, the names and the chemical symbols used for elements 104 to 109 were those recommended then by the Commission on Nomenclature of Inorganic Chemistry of the International Union of Pure and Applied Chemistry (IUPAC). Since then, unfortunately for the resulting confusion, the names were changed and moreover two of them were displaced [4] (see also AME2003, Part I, Section 6.5). The user should therefore be careful when comparing results between NUBASE'97 and the present NUBASE2003 for nuclides with  $Z \geq 104$ . The finally adopted names and symbols are: 104 rutherfordium (Rf), 105 dubnium (Db), 106 seaborgium (Sg), 107 bohrium (Bh), 108 hassium (Hs), and 109 meitnerium (Mt), while the provisional symbols Ea, Eb, . . . , Ei are used for elements 110, 111, . . . , 118.

Besides considering all nuclides for which at least one piece of information is experimentally available, we also included unknown nuclides - for which we give estimated properties - in order to ensure continuity of the set of the considered nuclides at the same time in  $N$ , in  $Z$ , in  $A$  and in  $N - Z$ . The chart of the nuclides defined this way has a smooth contour.

As far as possible, one standard deviations ( $1 \sigma$ ) are given to represent the uncertainties connected with the experimental values. Unfortunately, authors do not always define the meaning of the uncertainties they quote; under such circumstances, the uncertainties are assumed to be one standard deviations. In many cases, the uncertainties are not given at all; we then estimated them on the basis of the limitations of the method of measurement.

Values and errors that are given in the NUBASE table have been rounded, even if unrounded values were found in ENSDF or in the literature. In cases where the two

furthest-left significant digit in the error were larger than a given limit (30 for the energies, to maintain strict identity with AME2003, and 25 for all other quantities), values and errors were rounded off (see examples in the ‘Explanation of table’). In very few cases, when essential for traceability, we added a remark with the original value.

When no experimental data exist for a nuclide, values can often be estimated from observed trends in the systematics of experimental data. In the AME2003, masses estimated from systematic trends were already flagged with the symbol ‘#’. The use of this symbol has been extended in NUBASE to all other quantities and has the same meaning of indicating non-experimental information.

## 2.1. Mass excess

The mass excess is defined as the difference between the atomic mass (in mass units) and the mass number, and is given in keV for each nuclear state, together with its one standard deviation uncertainty. The mass excess values given in NUBASE are exactly those of the AME2003 evaluation, given in the second part of this issue.

It sometimes happens that knowledge of masses can yield information on the decay modes, in particular regarding nucleon-stability. Such information has been used here, as can be seen in the table for  $^{10}\text{He}$ ,  $^{19}\text{Na}$ ,  $^{39}\text{Sc}$ ,  $^{62}\text{As}$  or  $^{63}\text{As}$ . In some cases we rejected claimed observation of decay modes, when not allowed by energetic consideration. As an example, ENSDF2000 compiles for  $^{142}\text{Ba}$  five measurements of delayed neutron decay intensities, whereas  $Q(\beta^-n) = -2955(7)$  keV.

Figure 1 complements the main table in displaying the precisions on the masses, in a color-coded chart, as a function of  $N$  and  $Z$ .

## 2.2. Isomers

In the first version of NUBASE in 1997 [2], a simple definition for the excited isomers was adopted: they were states that live longer than 1 millisecond. Already in NUBASE97, we noticed that such a simple definition had several drawbacks, particularly for alpha and proton decaying nuclides: whereas for  $\beta$ -decay a limit of 1 millisecond was acceptable (the shortest-lived known  $\beta$ -decaying nuclide ( $^{35}\text{Na}$ ) has a half-life of 1.5 millisecond), for  $\alpha$  or proton decay, several cases are known where an isomer with a half-life far below 1 millisecond lives still longer than the ground-state.

As mentioned earlier, the definition of isomers is now extended to include a large number of excited states, with half-lives as short as 100 ns, that are of interest for mass spectrometric works at accelerators. Isomers are given in order of increasing excitation energy and identified by appending ‘ $m$ ’, ‘ $n$ ’, ‘ $p$ ’ or ‘ $q$ ’ to the nuclide name, e.g.  $^{90}\text{Nb}$  for the ground-state,  $^{90}\text{Nb}^m$  for the first excited isomer,  $^{90}\text{Nb}^n$  for the second

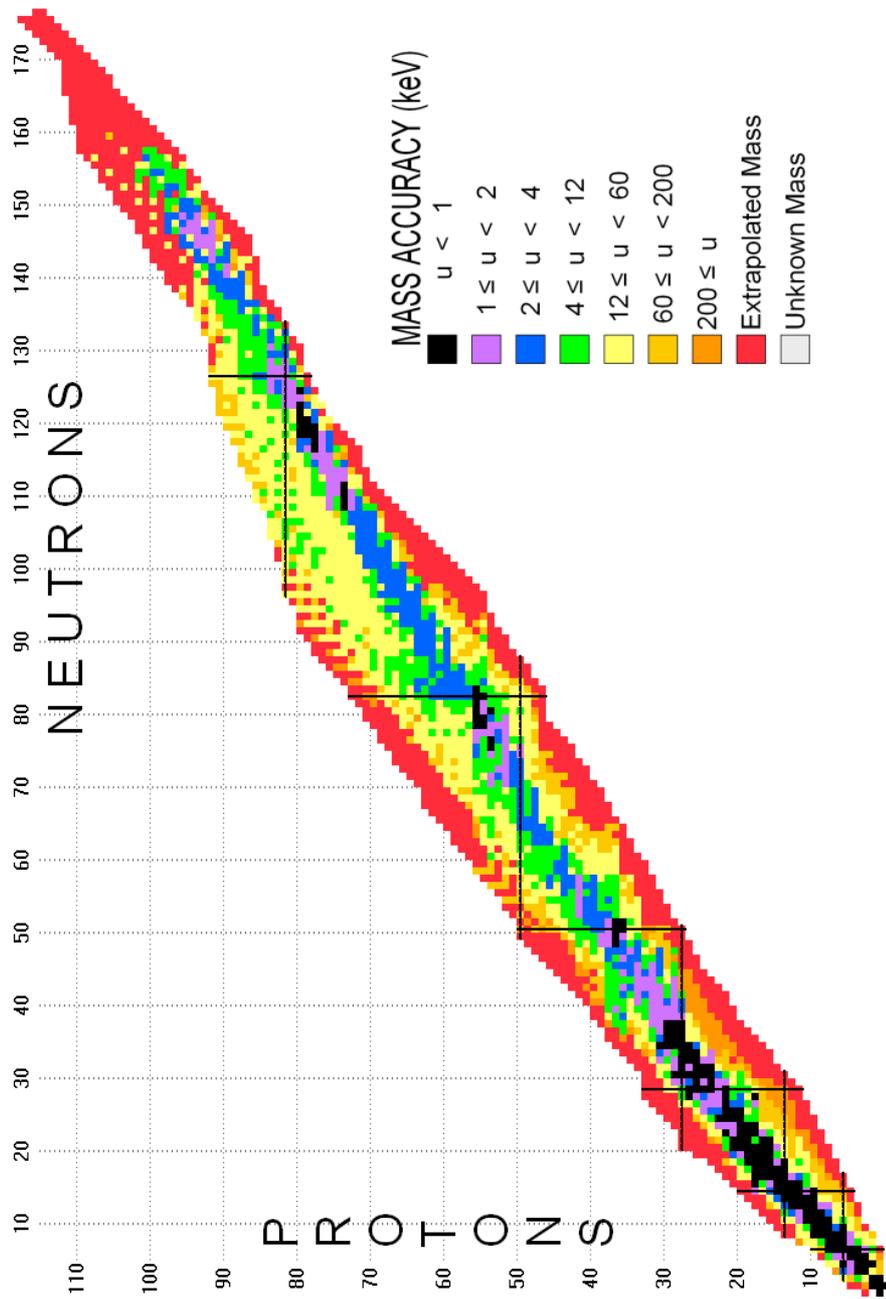


Figure 1: Chart of the nuclides for the precision 'u' on masses (created by NUCLEUS-AMDC).

one,  $^{90}\text{Nb}^p$  and  $^{90}\text{Nb}^q$  for respectively the third and fourth. In NUBASE97 we could not report in a normal way the third excited isomer of  $^{178}\text{Ta}$  with half-life 59 ms, because of poorness of notation; the new notation adopted here removes also such a limitation.

The excitation energy can be derived from a number of different experimental methods. When this energy is derived from a method other than  $\gamma$ -ray spectrometry, the origin is indicated by a two-letter code and the numerical value is taken from AME. Otherwise, the code is left blank and the numerical value is taken from ENSDF or from literature update.

When the existence of an isomer is under discussion (e.g.  $^{141}\text{Tb}^m$ ) it is flagged with ‘EU’ in the origin field to mean “existence uncertain”. A comment is generally added to indicate why its existence is questioned, or where this matter has been discussed. Depending on the degree of our confidence in this existence, we can still give a mass excess value and an excitation energy, or omit them altogether (e.g.  $^{138}\text{Pm}^n$ ). In the latter case, the mention “non-existent” appears in place of that excitation energy.

When an isomer has been reported, and later proved not to exist (e.g.  $^{184}\text{Lu}^m$ ), it is flagged with ‘RN’ in the origin field to mean “reported, non-existent”. In such case we give of course no mass excess value and no excitation energy, and, as in the case of the ‘EU’s above, they are replaced by the same mention “non-existent”.

*Note:* we have extended the use of the two flags ‘EU’ and ‘RN’ to cases where the discovery of a nuclide (e.g.  $^{260}\text{Fm}$ ) is questioned. In this case however we always give an estimate, derived from systematic trends, for the ground state masses.

In several cases, ENSDF gives a lower and a higher limit for an isomeric excitation energy. A uniform distribution of probabilities has been assumed which yields a value at the middle of the range and a  $1\sigma$  uncertainty of 29% of that range (cf. Appendix B of the AME2003, Part I, for a complete description of this procedure). An example is  $^{136}\text{La}$  for which it is known that the excited isomer lies above the level at 230.1 keV, but, as explained in ENSDF, there are good experimental indications that the difference between these two levels lies between 10 and 40 keV. We present this information as  $E = 255(9)$  keV. However, if that difference would have been derived from theory or from systematics, the resulting  $E$  is considered as non-experimental and the value flagged with the ‘#’ symbol.

In case that the uncertainty  $\sigma$  on the excitation energy  $E$  is relatively large compared to the value, the assignment to ground state and isomeric state is uncertain. If  $\sigma > E/2$  a flag is added in the NUBASE table.

As a result of this work, the orderings of several ground-states and isomeric-states have been reversed compared to those in ENSDF. They are flagged in the NUBASE table with the ‘&’ symbol. In several cases we found evidence for a state below the adopted ENSDF ground-state. Also, in many other cases, the systematics of nuclides with the same parities in  $N$  and  $Z$  strongly suggest that such a lower state should exist.

They have been added in the NUBASE table and can be located easily, since they are also flagged with the ‘&’ symbol. In a few cases, new information on masses can also lead to reversal of the level ordering. Thanks to the coupling of the NUBASE and the AME evaluations, all changes in level ordering are carefully synchronized.

#### *News on isomeric excitation energies*

Interestingly, the technique of investigating proton decay of very proton-rich nuclides gives information on isomeric excitation energies. Thus, such work on  $^{167}\text{Ir}$  [1997Da07] shows that it has an isomeric excitation energy  $E = 175.3(2.2)$  keV. This information is displayed by the ‘p’ symbol following the excitation energy. In addition, study of the  $\alpha$ -decay series of these activities not only showed that a number of  $\alpha$  lines earlier assigned to ground-states belong in reality to isomers, but also allowed to derive values for their excitation energies.

Another case of such a change is  $^{181}\text{Pb}$ . The  $\alpha$  decay half-life that was previously assigned to  $^{181}\text{Pb}^m$  is now assigned to the ground-state, following the work of Toth *et al.* [1996To01] who showed, first, that contrary to a previous work, there is no  $\alpha$  line at higher energy than the one just mentioned, and second, that the observed  $\alpha$  is in correlation with the decay of the daughter  $^{177}\text{Hg}$ , which is also most probably a  $5/2^-$  state.

### **2.3. Half-life**

For some light nuclei, the half-life ( $T_{1/2}$ ) is deduced from the level total width ( $\Gamma_{\text{cm}}$ ) by the equation  $\Gamma_{\text{cm}} T_{1/2} \simeq \hbar \ln 2$  :

$$T_{1/2} (\text{s}) \simeq 4.562 \cdot 10^{-22} / \Gamma_{\text{cm}} (\text{MeV}).$$

Quite often uncertainties for half-lives are given asymmetrically  $T_{-b}^{+a}$ . If these uncertainties are used in some applications, they need to be symmetrized. Earlier (cf. AME’95) a rough symmetrization was used: take the central value to be the mid-value between the upper and lower  $1\sigma$ -equivalent limits  $T + (a - b)/2$ , and define the uncertainty to be the average of the two uncertainties  $(a + b)/2$ . A strict statistical derivation (see Appendix) shows that a better approximation for the central value is obtained by using  $T + 0.64 \times (a - b)$ . The exact expression for the uncertainty is given in the Appendix.

When two or more independent measurements have been reported, they are averaged, while being weighed by their reported precision. While doing this, we consider the NORMALIZED CHI,  $\chi_n$  (or ‘consistency factor’ or ‘Birge ratio’), as defined in AME2003, Part I, Section 5.2. Only when  $\chi_n$  is beyond 2.5, do we depart from the statistical result, and adopt the external error for the average, following the same

policy as discussed and adopted in AME2003, Part I, Section 5.4. Very rarely, when the Birge ratio  $\chi_n$  is so large that we consider all errors given as non-relevant, do we adopt the arithmetic average (unweighed) for the result and the corresponding error (based on the dispersion of values). In all such cases, a remark is added to the data, giving the list of values that were averaged, and, when relevant, the value of the Birge ratio  $\chi_n$  and the reason for our choice.

In the case of experiments in which extremely rare events are observed, and where the results are very asymmetric, we did not average directly the half-lives derived from different works, but instead, when the information given in the papers was sufficient (e.g.  $^{264}\text{Hs}$  or  $^{269}\text{Hs}$ ), we combined the delay times of the individual events, as prescribed by Schmidt *et al* [1984Sc13].

Some measurements are reported as a range of values with most probable lower and upper limits. They are treated, as explained above (cf. Section 2.2), as a uniform distribution of probabilities with a value at the middle of the range and a  $1\sigma$  uncertainty of 29% of that range (cf. Appendix B of the AME2003 for a complete description of this procedure).

For some nuclides identified by using a time-of-flight spectrometer, an upper or a lower limit on the half-life is given.

i) For *observed* species, we give this important but isolated piece of information (lower limit) in place of the uncertainty on the half-life, and within brackets (e.g.  $^{36}\text{Mg}$ , p. 34). The user of our table should be careful in that this limit can be very far below the eventually measured half-life. To help to avoid confusion, we now give, in addition, an estimate (as always in the present two evaluations, flagged with #) for the half-life derived from trends in systematics.

ii) For nuclides sought for but *not observed*, we give the found upper limit in place of the half-life. Upper limits for undetected nuclides have been evaluated for NUBASE by F. Pougheon [1993Po.A], based on the time-of-flight of the experimental setup and the yields expected from the trends in neighboring nuclides (e.g.  $^{19}\text{Na}$ ).

When half-lives for nuclides with the same parities in  $Z$  and  $N$  are found to vary smoothly (see Fig. 2), interpolation or extrapolation is used to obtain reasonable estimates.

## 2.4. Spin and parity

As in ENSDF, values are presented without and with parentheses based upon strong and weak assignment arguments, respectively (see the introductory pages of Ref. [5]). Unfortunately, the latter include estimates from systematics or theory. Where we can distinguish them, we use parentheses if the so-called “weak” argument is an experimental one, but the symbol ‘#’ in the other cases. The survey might have not been complete, and the reader might still find non-flagged non-experimental cases (the

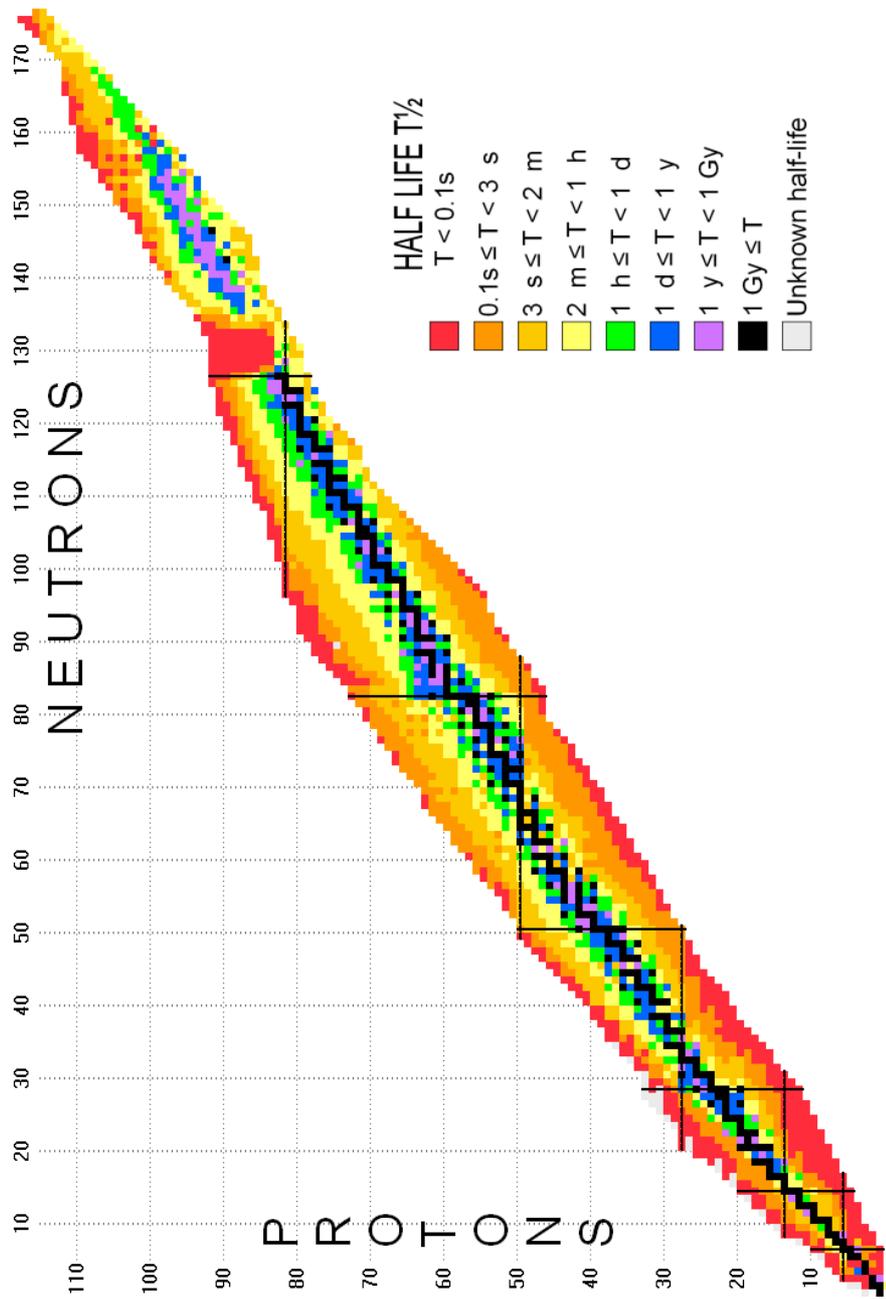


Figure 2: Chart of the nuclides for half-lives (created by NUCLEUS-AMDC).

authors will gratefully appreciate mention of such cases to improve future versions of NUBASE).

If spin and parity are not known from experiment, they can be estimated, in some cases, from systematic trends in neighboring nuclides with the same parities in  $N$  and  $Z$ . This is often true for odd- $A$  nuclides (see Fig. 3 and Fig. 4), but also, not so rarely, for odd–odd ones, as can be seen in Fig. 5. These estimated values are also flagged with the ‘#’ symbol. In several cases we replaced the ENSDF systematics by our own.

The review of nuclear radii and moments of Otten [1989Ot.A], in which the spins were compiled, was used to check and complete the spin values in NUBASE.

## 2.5. Decay modes and intensities

The most important policy, from our point of view, in coding the information for the decay modes, is in establishing a very clear distinction between a decay mode that is energetically allowed but not yet experimentally observed (represented by a question mark alone, which thus refers to the decay mode itself), and a decay mode that is actually observed but for which the intensity could not be determined (represented by ‘=?’, the question mark referring here to the quantity after the equal sign).

As in ENSDF, no corrections have been made to normalize the primary intensities to 100%.

Besides direct updates from the literature, we also made use of partial evaluations by other authors (with proper quotation). They are mentioned below, when discussing some particular decay modes.

### *The $\beta^+$ decay*

In the course of our work we refined some definitions and notations for the  $\beta^+$  decay, in order to present more clearly the available information. We denote with  $\beta^+$  the decay process that includes both electron capture, denoted  $\varepsilon$ , and the decay by positron emission, denoted  $e^+$ . One can then symbolically write:  $\beta^+ = \varepsilon + e^+$ . As is well known, for an available energy below 1022 keV, only electron capture  $\varepsilon$  is allowed; above that value both processes compete.

*Remark:* this notation is **not** the same as the one implicitly used in ENSDF, where the combination of both modes is denoted “EC+B+”.

When both modes compete, the separated intensities are not always available from experiment. Most of the time, separated values in ENSDF are calculated ones. In continuation of one of our general policies, in which we retain whenever possible only experimental information, we decided not to retain ENSDF’s calculated separated values (which are scarce and not always updated). Most often, it is in some very particular cases that the distinction is of importance, like in the case of rare or extremely rare processes (e.g.  $^{91}\text{Nb}$ ,  $^{54}\text{Mn}$ ,  $^{119}\text{Te}^m$ ). Then, the use of our notation is useful.

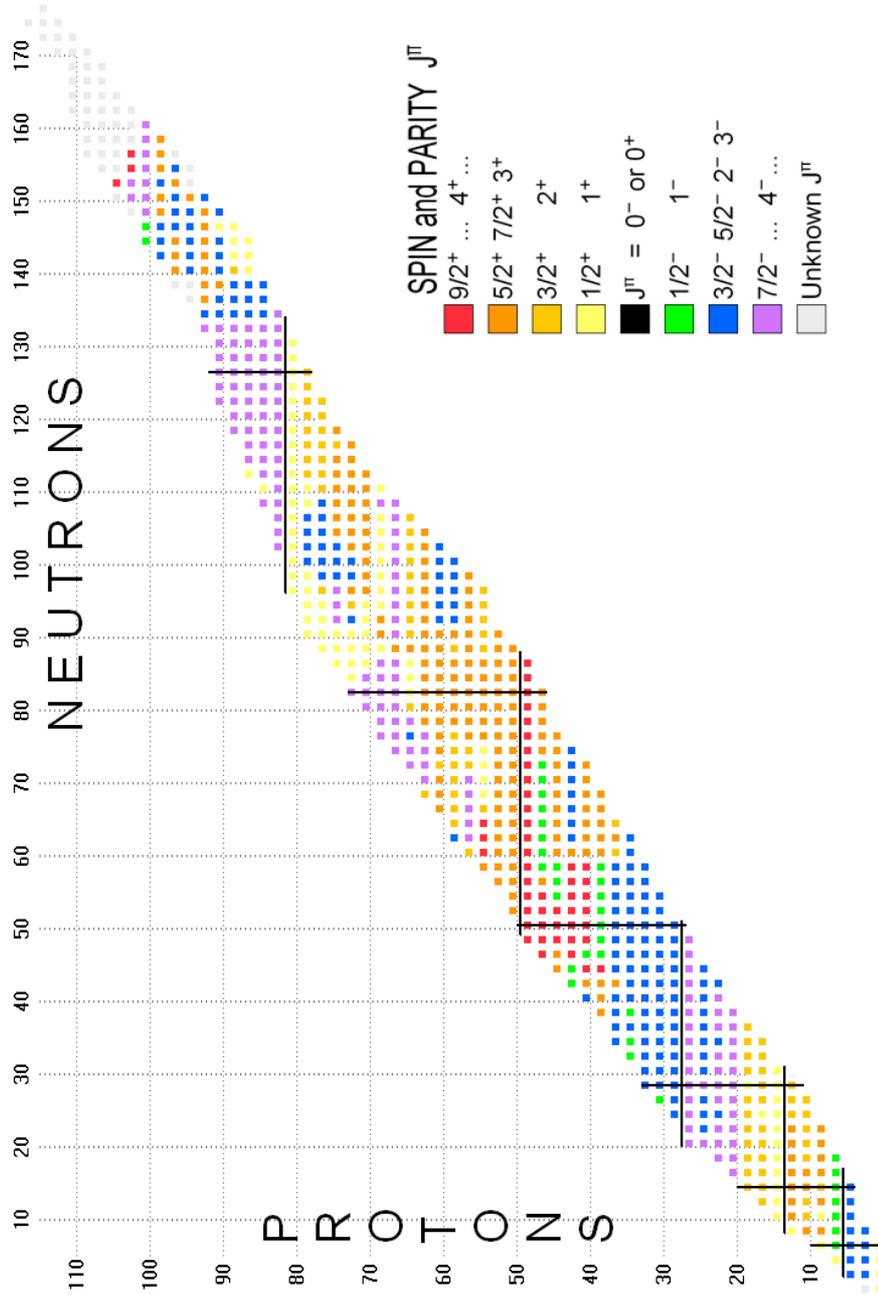


Figure 3: Chart of the nuclides for spins and parities. Shown are only the odd-Z even-N nuclides (created by NUCLEUS-AMDC).

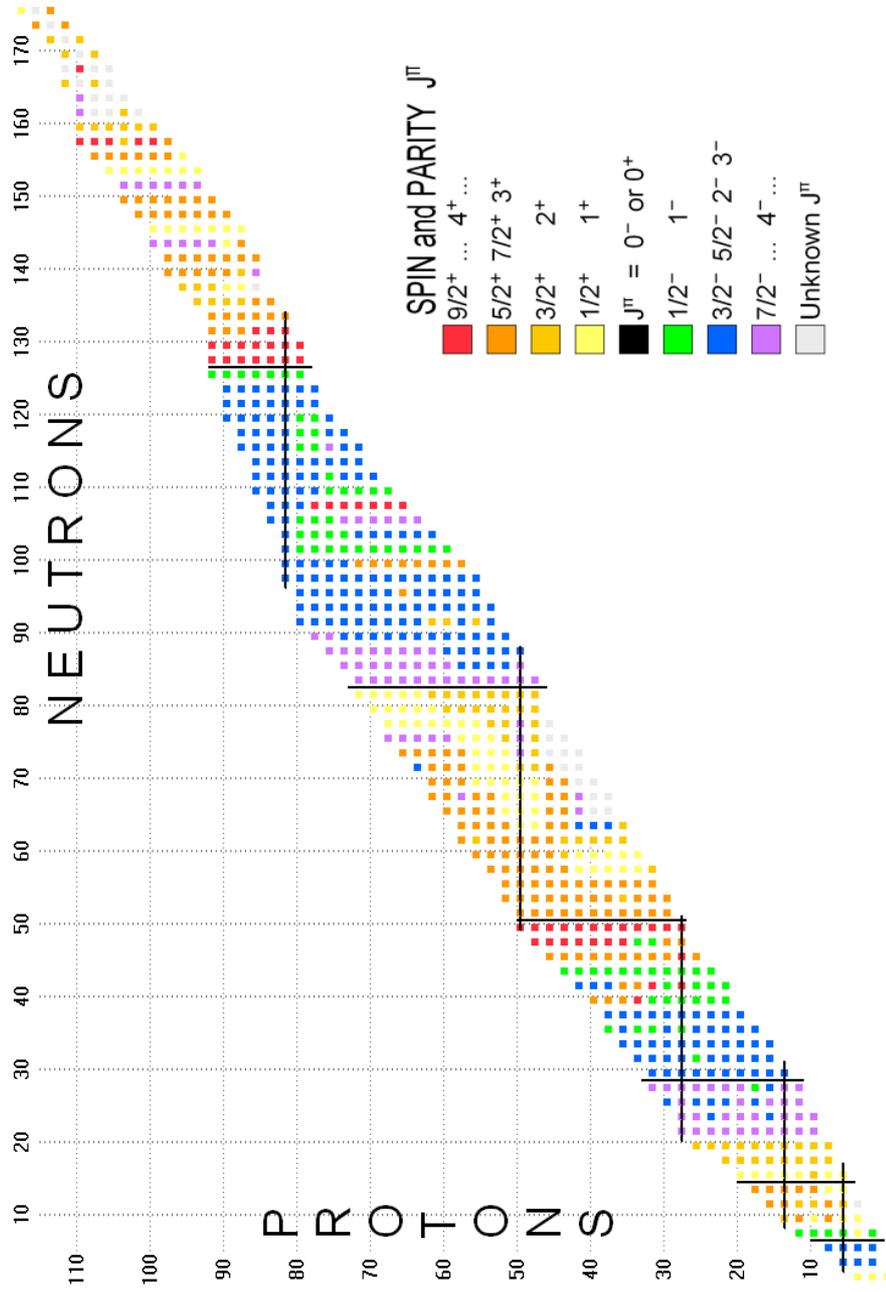


Figure 4: Chart of the nuclides for spins and parities. Shown are only the even- $Z$  odd- $N$  nuclides (created by NUCLEUS-AMDC).

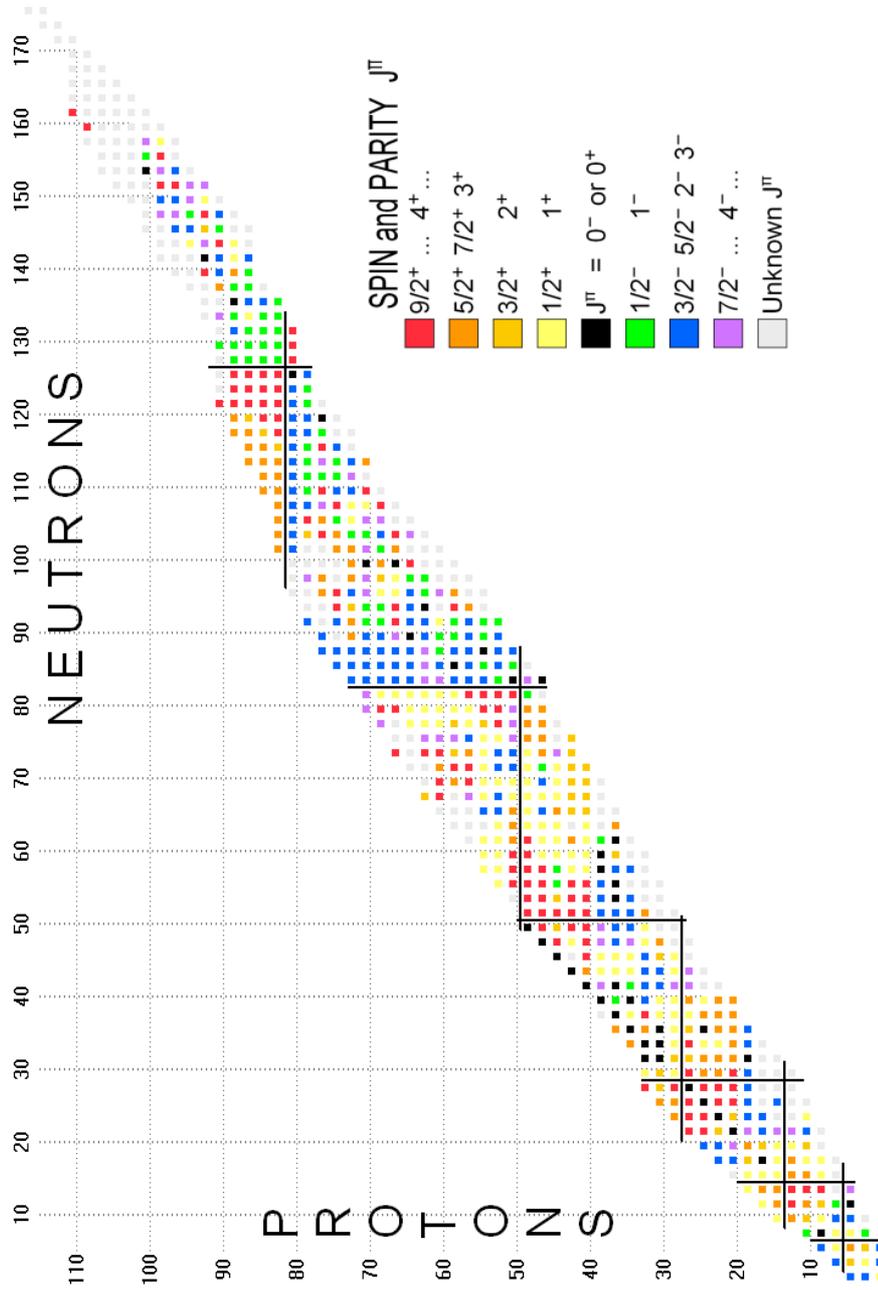


Figure 5: Chart of the nuclides for spins and parities. Shown are only the odd-Z odd-N nuclides (created by NUCLEUS-AMDC).

In the same line, we give both electron capture  $\varepsilon$ -delayed fission and the positron  $e^+$ -delayed fission with the same symbol  $\beta^+$ SF.

#### *The double- $\beta$ decay*

In the course of our work we found that half-lives for double- $\beta$  decay were not always given in a consistent way in ENSDF. For NUBASE we decided to give only half-life values or upper-limits related to the dominant process, which is in general the two-neutrino gs-gs transition (one exception may be  $^{98}\text{Mo}$ , for which the neutrinoless decay is predicted to be faster, see [2002Tr04]). No attempt was made to convert to the same statistical confidence level (CL) upper limit results given by different authors.

The excellent recent compilation of Tretyak and Zdesenko [2002Tr04] was of great help in this part of our work.

#### *The $\beta$ -delayed decays*

For delayed decays, intensities have to be considered carefully. By definition, the intensity of a decay mode is the percentage of decaying nuclei in that mode. But traditionally, the intensities of the pure  $\beta$  decay and of those of the delayed ones are summed to give an intensity that is assigned to the pure  $\beta$  decay. For example, if the  $(A,Z)$  nuclide has a decay described, according to the tradition, by ' $\beta^-=100$ ;  $\beta^-n=20$ ', this means that for 100 decays of the parent  $(A,Z)$ , 80  $(A,Z+1)$  and 20  $(A-1,Z+1)$  daughter nuclei are produced and that 100 electrons and 20 delayed-neutrons are emitted. A strict notation, following the definition above, would have been in this case ' $\beta^-=80$ ;  $\beta^-n=20$ '. However we decided to follow the tradition and use in our work the notation: ' $\beta^-=100$ ;  $\beta^-n=20$ '.

This also holds for more complex delayed emissions. A decay described by: ' $\beta^-=100$ ;  $\beta^-n=30$ ;  $\beta^-2n=20$ ;  $\beta^-\alpha=10$ ' corresponds to the emission of 100 electrons,  $(30+2\times 20=70)$  delayed-neutrons and 10 delayed- $\alpha$  particles; and in terms of residual nuclides, to 40  $(A,Z+1)$ , 30  $(A-1,Z+1)$ , 20  $(A-2,Z+1)$  and 10  $(A-4,Z-1)$ . More generally,  $P_n$ , the number of emitted neutrons per 100 decays, can be written:

$$P_n = \sum_i i \times \beta_{in}^-;$$

and similar expressions for  $\alpha$  or proton emission. The number of residual  $\beta$  daughter  $(A,Z+1)$  is:

$$\beta^- - \sum_i \beta_{in}^- - \sum_j \beta_{j\alpha}^- - \dots$$

Another special remark concerns the intensity of a particular  $\beta$ -delayed mode. The primary  $\beta$ -decay populates several excited states in the  $\beta$ -daughter, that will further decay by particle emission. However, in the case where the daughter's ground state also decays by the same particle emission, some authors included its decay

in the value for the concerned  $\beta$ -delayed intensity. We decided not to do so for two reasons. Firstly, because the energies of the particles emitted from the excited states are generally much higher than that from the ground-state, implying different subsequent processes. Secondly, because the characteristic times for the decays from the excited states are related to the parent, whereas those for the decays from the daughter's ground state are due to the daughter. For example  ${}^9\text{C}$  decays through  $\beta^+$  mode with an intensity of 100% of which 12% and 11% to two excited p-emitting states in  ${}^9\text{B}$ , and 17% to an  $\alpha$ -emitting state. We give thus  $\beta^+_{\text{p}}=23\%$  and  $\beta^+_{\alpha}=17\%$ , from which the user of our table can derive a 60% direct feeding of the ground-state of  ${}^9\text{B}$ . In a slightly different example,  ${}^8\text{B}$  decays only to two excited states in  ${}^8\text{Be}$  which in turn decay by  $\alpha$  and  $\gamma$  emission, but not to the  ${}^8\text{Be}$  ground-state. We write thus  $\beta^+=100\%$  and  $\beta^+_{\alpha}=100\%$ , the difference of which leaves 0% for the feeding of the daughter's ground state.

Finally, we want to draw to the attention of the user of our table, that the percentages are, by definition, related to 100 decaying nuclei, not to the primary beta-decay fraction. An illustrative example is given by the decay of  ${}^{228}\text{Np}$ , for which the delayed-fission probability is given in the original paper as 0.020(9)% [1994Kr13], but this number is relative to the  $\epsilon$  process, the intensity of which is 59(7)%. We thus renormalized the delayed-fission intensity to 0.012(6)% of the total decay.

In collecting the delayed proton and  $\alpha$  activities, the remarkable work of Hardy and Hagberg [1989Ha.A], in which this physics was reviewed and discussed, was an appreciable help in our work. The review of Honkanen, Äystö and Eskola [6] on delayed-protons has also been verified.

Similarly, the review of delayed neutron emission by Hansen and Jonson [1989Ha.B] was carefully examined and used in our table, as well as the evaluation of Rudstam, Aleklett and Sihver [1993Ru01].

## 2.6. Isotopic abundances

Isotopic abundances are taken from the compilation of K.J.R. Rosman and P.D.P. Taylor [1998Ro45] and are listed in the decay field with the symbol IS. They are displayed as given in [1998Ro45], i.e. we did not even apply our rounding policy.

## 2.7. References

The year of the archival file is indicated for the nuclides evaluated in ENSDF; otherwise, this entry is left blank.

References for all of the experimental updates are given by the NSR key number [3], and listed at the end of this issue (p. 579). They are followed by one, two or three one-letter codes which specify the added or modified physical quantities (see the

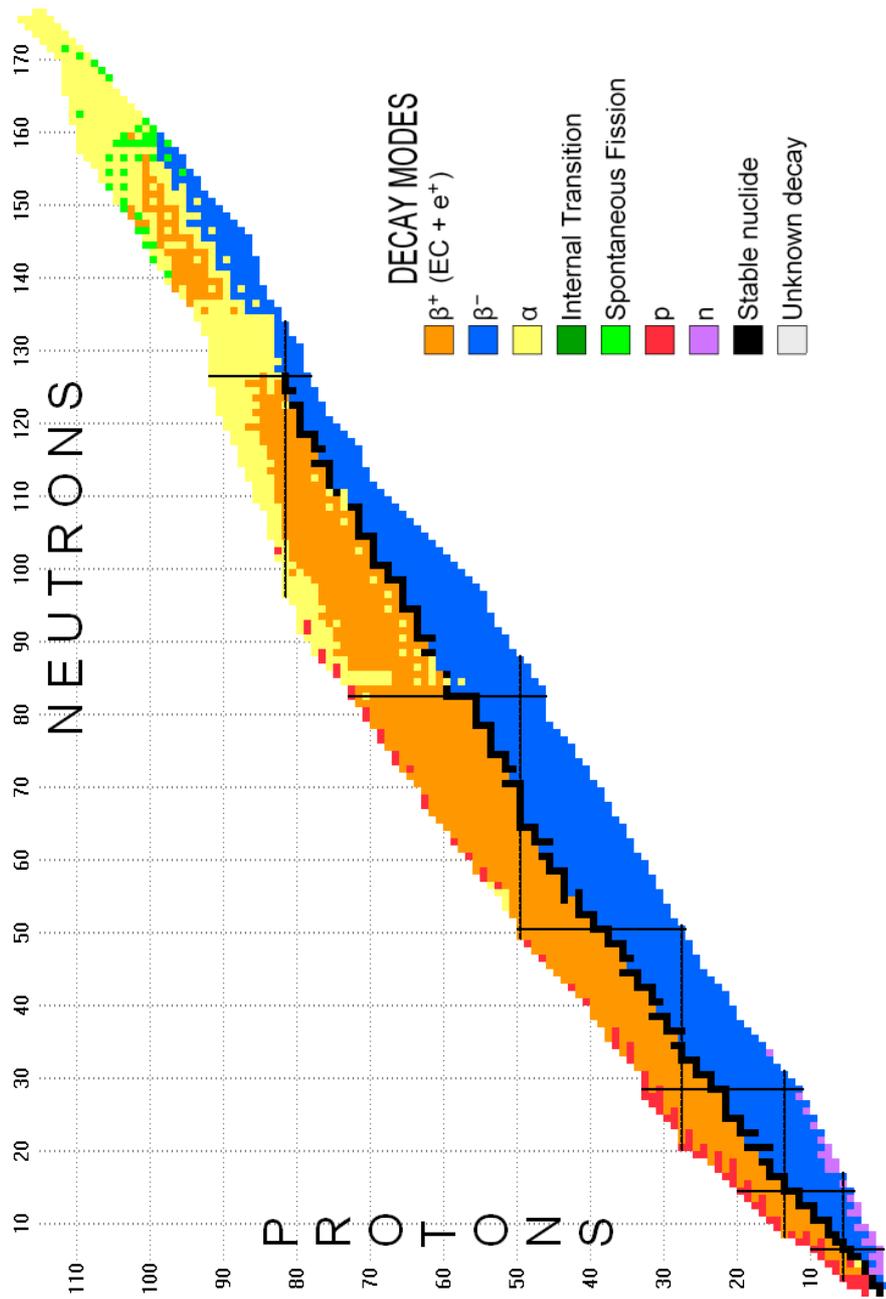


Figure 6: Chart of the nuclides for decay modes (created by NUCLEUS-AMDC).

Explanation of Table). In cases where more than one reference is needed to describe the updates, they are given in a remark. No reference is given for systematic values. The ABBW reference key is used in cases where it may not appear unambiguously that re-interpretations of the data were made by the present authors.

### 3. Updating procedure

NUBASE is updated via two routes: from ENSDF after each new  $A$ -chain evaluation (or from the bi-annual releases), and directly from the literature.

ENSDF files are retrieved from NNDC using the on-line service [1] and transferred through the Internet. Two of the present authors [7] developed programs to successively:

- check that each  $Z$  in the  $A$ -chain has an ‘adopted levels’ data set; if not, a corresponding data set is generated from the ‘decay’ or ‘reaction’ data set,
- extract the ‘adopted levels’ data sets from ENSDF,
- extract from these data sets the required physical quantities, and convert them into a format similar to the NUBASE format.

The processed data are used to update manually the previous version of NUBASE. This step is done separately by the four authors and cross-checked until full agreement is reached.

The ENSDF is updated generally by  $A$ -chains, and, more recently, also by individual nuclides. Its contents however is very large, since it encompasses all the complex nuclear structure and decay properties. This is a huge effort, and it is no wonder that some older data (including annual reports, conference proceedings, and theses) are missing, and that some recent data have not yet been included. Where we notice such missing data, they are analyzed and evaluated, as above, independently by the four authors and the proposed updates are compared. Most often these new data are included in the next ENSDF evaluation and the corresponding references can be removed from the NUBASE database.

### 4. Distribution and displays of NUBASE

Full content of the present evaluation is accessible on-line at the web site of the Atomic Mass Data Center (AMDC) [8] through the *World Wide Web*. An electronic ASCII file for the NUBASE table, for use with computer programs, is also distributed by the AMDC. This file will **not** be updated, to allow stable reference data for calculations. Any work using that file should make reference to the present paper and not to the electronic file.

The contents of NUBASE can be displayed by a Java program JVNUBASE [9] through the *World Wide Web* and also with a PC-program called “NUCLEUS” [10]. Both can

be accessed or downloaded from the AMDC. They will be updated regularly to allow the user to check for the latest available information in NUBASE.

## 5. Conclusions

A ‘horizontal’ evaluated database has been developed which contains most of the main properties of the nuclides in their ground and isomeric states. These data originate from a critical compilation of two evaluated datasets: the ENSDF, updated and completed from the literature, and the AME. The guidelines in setting up this database were to cover as completely as possible all the experimental data, and to provide proper reference for those used in NUBASE and not already included in ENSDF; this traceability allows any user to check the recommended data and, if necessary, undertake a re-evaluation.

As a result of this ‘horizontal’ work, a greater homogeneity in data handling and presentation has been obtained for all of the nuclides. Furthermore, isomeric assignments and excitation energies have been reconsidered on a firmer basis and their data improved.

It is expected to follow up this second version of NUBASE with improved treatments. Among them, we plan to complete the extension due to the new definition of isomer to states with half-lives between 100 ns and 1 millisecond that are available at the large-scale facilities. Another foreseeable implementation would be to provide the main  $\alpha$ ,  $\gamma$ , conversion and X-ray lines accompanying the decays. NUBASE could also be extended to other nuclear properties: energies of the first  $2^+$  states in even-even nuclides, radii, moments . . . An interesting feature that is already implemented, but not yet checked sufficiently to be included here, is to give for each nuclide, in ground or isomeric-state, the year of its discovery.

## 6. Acknowledgements

We wish to thank our many colleagues who answered our questions about their experiments and those who sent us preprints of their papers. Continuous interest, discussions, suggestions and help in the preparation of the present publication by C. Thibault were highly appreciated. We appreciate the help provided by J.K. Tuli in solving some of the puzzles we encountered. Special thanks are due to S. Audi for the preparation of the color figures from the NUCLEUS program, and to C. Gaulard and D. Lunney for careful reading of the manuscript. A.H.W. expresses his gratitude to the NIKHEF-K laboratory and especially to Mr. K. Huyser for his continual help, and J.B. to the ISN-Grenoble and DRFMC-Grenoble laboratories for permission to use their facilities.

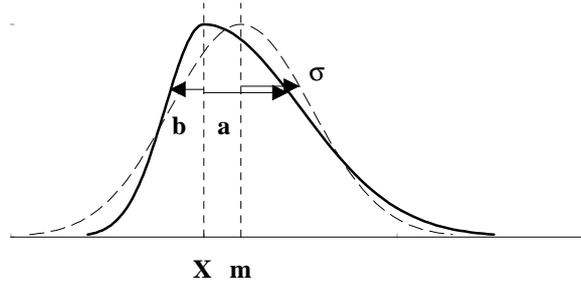


Figure 7: Simulated asymmetric probability density function (heavy solid line) and the equivalent symmetric one (dashed line).

### Appendix A. Symmetrization of asymmetric uncertainties

Experimental data are sometimes given with asymmetric uncertainties,  $X_{-b}^{+a}$ . If these data are to be used with other ones in some applications, their uncertainties may need to be symmetrized. A simple method (Method 1), used earlier, consisted in taking the central value to be the mid-value between the upper and lower  $1\sigma$ -equivalent limits  $X + (a - b)/2$ , and define the uncertainty to be the average of the two uncertainties  $(a + b)/2$ .

An alternative method (Method 2) is to consider the random variable  $x$  associated with the measured quantity. For this random variable, we assume the probability density function to be an asymmetric normal distribution having a modal (most probable) value of  $x = X$ , a standard deviation  $b$  for  $x < X$ , and a standard deviation  $a$  for  $x > X$  (Fig. 7). Then the average value of this distribution is

$$\langle x \rangle = X + \sqrt{2/\pi} (a - b),$$

with variance

$$\sigma^2 = (1 - 2/\pi) (a - b)^2 + ab. \quad (1)$$

The median value  $m$  which divides the distribution into two equal areas is given, for  $a > b$ , by

$$\operatorname{erf}\left(\frac{m - X}{\sqrt{2}a}\right) = \frac{a - b}{2a}, \quad (2)$$

and by a similar expression for  $b > a$ .

We define the equivalent symmetric normal distribution we are looking for as a distribution having a mean value equal to the median value  $m$  of the previous distribution with same variance  $\sigma$ .

Table A. Examples of treatment of asymmetric uncertainties for half-lives. Method 1 is the classical method, used previously, as in the AME'95. Method 2 is the one developed in this Appendix and used for half-lives and intensities of the decay modes.

Nuclide	Original $T_{1/2}$	Method 1	Method 2
$^{76}\text{Ni}$	240+550–190 ms	$420 \pm 370$	$470 \pm 390$
$^{222}\text{U}$	1.0+1.0–0.4 $\mu\text{s}$	$1.3 \pm 0.7$	$1.4 \pm 0.7$
$^{264}\text{Hs}$	327+448–120 $\mu\text{s}$	$490 \pm 280$	$540 \pm 300$
$^{266}\text{Mt}$	1.01+0.47–0.24 ms	$1.1 \pm 0.4$	$1.2 \pm 0.4$

If the shift  $m - X$  of the central value is small compared to  $a$  or  $b$ , expression (2) can be written [11]:

$$m - X \simeq \sqrt{\pi/8} (a - b) \simeq 0.6267 (a - b).$$

In order to allow for a small non-linearity that appears for higher values of  $m - X$ , we adopt for Method 2 the relation

$$m - X = 0.64 (a - b).$$

Table A illustrates the results from both methods. In NUBASE, Method 2 is used for the symmetrization of asymmetric half-lives and of asymmetric decay intensities.

## References

References quoted in the text as [1993Po.A] or [2002Tr04] (NSR style) are listed under "References used in the AME2003 and the NUBASE2003 evaluations", p. 579.

- [1] T.W. Burrows, Nucl. Instrum. Meth. 286 (1990) 595;  
<http://www.nndc.bnl.gov/>
- [2] G. Audi, O. Bersillon, J. Blachot and A.H. Wapstra, Nucl. Phys. A 624 (1997) 1;  
<http://csnwww.in2p3.fr/AMDC/nubase/nubase97.pdf>
- [3] Nuclear Structure Reference (NSR): a computer file of indexed references maintained by NNDC, Brookhaven National Laboratory;  
<http://www2.nndc.bnl.gov/nsr/>
- [4] Commission on Nomenclature of Inorganic Chemistry, Pure and Applied Chemistry 69 (1997) 2471.
- [5] General Policies, Nuclear Data Sheets, 71(1994) v.

- [6] J. Honkanen, J. Äystö and K. Eskola, Phys. Scr. 34 (1986) 608.
- [7] O. Bersillon and J. Blachot, NEANDC(E) 246/L, INDC(FR) 071/L, September 1991.
- [8] The NUBASE2003 files in the electronic distribution and complementary information can be retrieved from the Atomic Mass Data Center (AMDC) through the *Web*: <http://csnwww.in2p3.fr/amdc/>
- [9] E. Durand, Report CSNSM 97-09, July 1997; <http://csnwww.in2p3.fr/AMDC/nucleus/stg-durand.doc>
- [10] B. Potet, J. Dufflo and G. Audi, Proceedings ENAM'95 conference, Arles, June 1995, p. 151; <http://csnwww.in2p3.fr/AMDC/nucleus/arlnucleus.ps>
- [11] R.D. Evans, The Atomic Nucleus (McGraw-Hill, New York, 1955) p. 766.